AUSTRALIAN RESEARCH TO SUPPORT THE IHRA VEHICLE COMPATIBILITY WORKING GROUP

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ABSTRACT

Frontal crashes cause the majority of serious injury and fatalities on the roads. It is now accepted that one of the main goals in improving vehicle compatibility is to design vehicles to maximise structural interaction of vehicles with different geometry, mass and stiffness. A compatibility test procedure must be able to assess the shear connections of the vehicle front structure as well as provide for correct energy management between dissimilar crash partners so as to guarantee passenger compartment integrity, which is particularly important in the smaller vehicle. This paper details the research conducted by the Australian Department of Transport and Regional Services to examine the feasibility of a constant energy compatibility test using the Renault Progressive Deformable Barrier (PDB) [1]. This work has been provided to the IHRA Vehicle Compatibility Working Group to consider in its deliberations to develop a vehicle compatibility test.

INTRODUCTION

Vehicle compatibility is about minimising the injury outcomes for all occupants when vehicles of different mass, stiffness and geometry crash into each other.

In general, the bigger the vehicle, the heavier and stiffer it is. In the case of light trucks, vans and 4WDs, they also tend to be higher off the ground. The design features of the striking vehicle that influence the injury outcome in the struck vehicle vary depending on the type of impact. In frontal impacts, mass, stiffness and geometry of both vehicles have an effect. For example, the crush structures of 4WDs tend to be high off the ground and will miss the lower crush structures of passenger cars. This overloads the upper crush structure of the passenger car and causes intrusion at dashboard level exposing the head and thorax to injury.

Current regulatory and consumer crash tests only ensure that the vehicle being tested is capable of absorbing its own kinetic energy – self-protection. These tests do not predict how vehicles of different mass, stiffness and geometry will interact when they crash into each other in the real world – vehicle compatibility.

The Australian Department of Transport and Regional Services (DOTARS) has done considerable testing to support international research to develop a vehicle compatibility test procedure. A range of research projects have been conducted to improve the understanding of vehicle compatibility with results being shared through the International Harmonised Research Activities (IHRA) Compatibility Working Group.

This paper details the compatibility research program being undertaken by DOTARS with assistance from Fuji Heavy Industries (Subaru), Ford Motor Company, Renault and the US National Highway Traffic Safety Administration.

CURRENT FRONTAL CRASH REGULATIONS

Frontal crashes cause the majority of serious injury and fatalities on the roads. These frontal crashes consist of a mixture of those that involve most of the front structure (high deceleration) and those that only involve part of the front structure (high intrusion).

Two Australian Design Rules (ADRs) have been introduced to improve occupant protection in these 2 types of frontal crashes. These were ADR 69/00 – Full Frontal Impact Occupant Protection introduced in July 1995 for high deceleration type crashes and ADR 73/00 – Offset Frontal Impact Occupant Protection introduced in January 2000 for high intrusion type crashes. Major developed countries around the world have adopted at least one of the test procedures specified in these ADRs.

Both these ADRs require testing the subject vehicle into a fixed barrier. In the case of ADR 73/00, there is a piece of aluminium honeycomb in front of the rigid barrier block. In addition, consumer crash testing (New Car Assessment Program – NCAP) is conducted in Australia and elsewhere utilising either or both the test procedures defined in ADRs 69/00 and 73/00 but using a higher test speed – at 56 km/h for ADR 69 and 64 km/h for ADR 73/00.

In an ideal world, the full frontal rigid barrier test in ADR 69/00 would represent two identical vehicles each travelling at 50 km/h crashing into each other with full engagement of their front structures.

In developing ADR 73/00, researchers used a baseline test of 2 identical vehicles crashing into each other with 50% overlap while both travelling at 50 km/h. The offset deformable barrier test was chosen at 40% overlap because the outermost 10% or so of a modern passenger car is not load-bearing, other than perhaps the wheel/tyre assembly. The test speed was increased to 56 km/h to account for the energy absorption of the aluminium honeycomb although Australia believed it should have been 60 km/h to better match the intrusions seen in car to car tests. There is now a move internationally to increase the regulatory test speed to 60 km/h.

The use of an aluminium honeycomb barrier for the offset frontal test was to reduce the high initial decelerations seen in the full overlap test into a rigid barrier which were used to initiate crush of the stiff front longitudinals. Tests of good performing cars in full frontal rigid wall tests indicated that when they crashed into each other at reduced overlaps, there was seldom perfect interaction of the stiff crush zones. In extreme cases, the longitudinals did not crush but transferred the crash energy to cause collapse of the vehicle's own relatively weak passenger compartment.

It was hoped that the Offset Deformable Barrier (ODB) test would drive manufacturers to design more homogeneous front structures, improved load spreading and stiffer passenger compartments to reduce intrusion.

The impact speeds of both the ODB and full overlap rigid barrier tests are fixed irrespective of the vehicle's mass. Therefore, heavier vehicles have to dissipate more kinetic energy. While both light and heavier vehicles appear to have become stiffer and heavier, it is unclear whether their relative stiffnesses have changed. Moreover, it is unknown whether newer structural designs have been driven in a direction that improves their performance in real world crashes.

The NCAP ODB test at 64 km/h sees most vehicles bottoming out the ODB thus allowing the front structures to contact the rigid block behind – there is evidence that some vehicle designs are using this resulting high deceleration to initiate crush of the front structure (the very thing the ODB test was designed to avoid).

All these tests focus on "self-protection" – that is how the vehicle model being tested performs when it has to manage its own crash energy. Unfortunately, identical vehicles seldom crash into each other in real life, therefore the challenge is to provide improved occupant protection to occupants of vehicles when colliding with vehicles that are of different size, geometry and mass – so called "Vehicle Compatibility". There are no regulations covering vehicle compatibility currently.

AUSTRALIAN NEW VEHICLE SALES TRENDS

The last 10 years in Australia has seen a polarisation of new passenger car sales where people are buying small (<1150 kg kerb mass) and large (>1300 kg kerb mass) cars with the medium car market shrinking significantly. Figure 1 shows the new vehicle sales figures for Australia from January to July 2002.

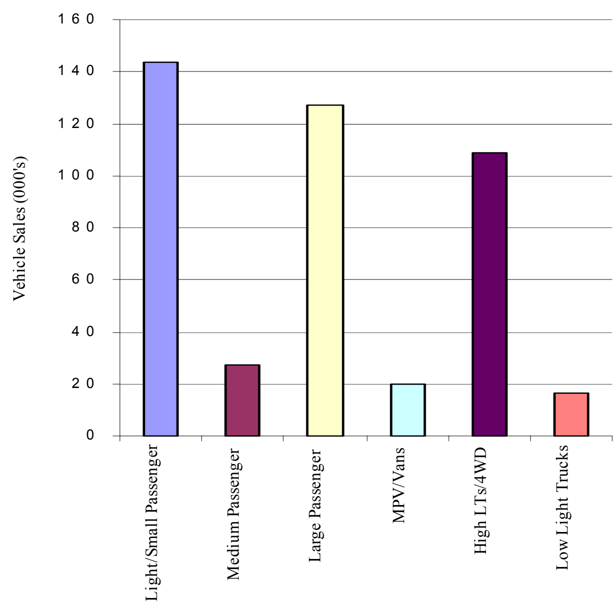

Figure 1. New Vehicle Sales to July 2002.

Large 4WDs (Toyota Landcruiser, Nissan Patrol, Mitsubishi Pajero etc) sales have been strong but relatively stagnant. MPV and van sales also appear to be fairly stagnant. However, sales of small 4WDs (Subaru Forester, Toyota RAV4, Honda CRV, LandRover Freelander, etc) have begun to increase significantly, particularly in recent years. While they are not as stiff as the large, body-on-frame 4WDs, their front structures are at similar heights and become incompatible with passenger car crash partners in both side and frontal impacts.

Assuming the average fleet age of around 11 years, the above new vehicle sales trend paints a worrying picture of the Australian fleet composition for crash compatibility around 2010.

COMPATIBILITY REQUIREMENTS

Introduction

The specifications for a compatibility test procedure are not yet defined. However, the guiding principles being aimed for are:

- Improve structural interaction of vehicles of different geometry.
- Control stiffness by limiting force transfer
- Set a minimum passenger compartment stiffness.

Some manufacturers have already taken upon themselves to increase passenger compartment stiffness particularly in their small cars. They are assuming that controlling the front stiffness of different sized vehicles and improving structural interaction may be difficult to achieve in the short term. Therefore increasing the passenger compartment stiffness may lead to the best short-term solution in improving small car safety.

There are 3 main compatibility issues that need to be addressed in developing a compatibility test:

- Mass incompatibility
- Stiffness incompatibility – both front crush structures and passenger compartment
- Geometric incompatibility

These 3 issues will be discussed under the topics of structural interaction and energy management.

Structural Interaction

One of the main goals in improving vehicle compatibility is to design vehicle front structures to maximise the interaction of vehicles with different architecture/geometry. Only by guaranteeing good structural interaction can the crush structures of different opposing vehicles be used up efficiently. As more research is being carried out, it is becoming clear that whatever test is developed must introduce vertical and lateral shear into the vehicle front structure.

The Renault Progressive Deformable Barrier (PDB) [1] has upper and lower load paths of different stiffnesses. These load paths also become progressively stiffer (by chemically etching the honeycomb) as the PDB is crushed. This appears to offer some form of test of the vertical connections between the upper and lower load paths of a vehicle.

However, the lateral stiffness of each load path in the PDB is constant, therefore an offset test is proposed to induce lateral shear into the test vehicle.

Energy Management

After ensuring good structural interaction, the question of managing the different kinetic energies of vehicles of various masses when they collide in the real world must be considered.

Renault suggests that it is the different stiffnesses of vehicle front structures that is the problem, saying that heavier vehicles have stiffer front ends because they have to absorb more energy in a self protection test.

For compatibility the basic requirement is that lighter vehicles need to be capable of managing the kinetic energy of the heaviest crash partner that a compatibility test aims to provide protection against.

COMPATIBILITY TEST PROPOSAL

In addition to a compatibility test, a separate assessment of self protection needs to be retained to ensure that heavy vehicles are not made too soft and light vehicles are not made too stiff. This will prevent the trade off of intrusion injuries for deceleration injuries and vice versa in vehicles of different sizes. It is proposed that this be the full frontal rigid barrier test specified in ADR 69, and the offset deformable barrier test in ADR 73 but at 60 km/h. Therefore three tests are proposed:

1. The first test deals with the issues of structural interaction and energy management by using the Renault PDB as the basis for a constant kinetic energy test method. The lighter the vehicle, the higher the test speed and vice versa.

– Assume that a test into the PDB at 60 km/h at 40% overlap is representative of a car to car

test at 100 km/h closing speed at 50% overlap.
– Choose the average passenger car fleet mass appropriate for the region, say 1600 kg for Australia.
– The above defines the baseline kinetic energy that vehicles of different masses need to dissipate and therefore defines the mass dependent test speed.
– Define a corridor for the force imparted on the barrier by the vehicle during the crash test as measured by the load cell wall.
– There may be another assessment method (eg homogeneity) using the deformed PDB's profile.

2. A full frontal rigid barrier self-protection test as specified in ADR 69 at 50 km/h.

3. An offset deformable barrier self-protection test as specified in ADR 73 but at 60 km/h.

All crash tests to be conducted with restrained Hybrid III dummies in the front outboard seating positions measuring current injury criteria in ADR 73.

The rationale for this proposal is:

- The energy equivalent test using instrumented dummies and specifying injury criteria should increase the passenger compartment stiffnesses of small vehicles and reduce their susceptibility to intrusion based injuries when colliding with larger, heavier vehicles.
- Specifying a force corridor, measured by the load cells behind the PDB, should force vehicle designs towards having similar front-end stiffnesses – "softening" the front-ends of larger vehicles.
- These factors should improve homogeneity and drive designs to have good vertical and lateral connections and improve structural interaction.
- The two separate self protection tests are needed to ensure that heavy vehicles are not made too soft and light vehicles are not made too stiff. This will prevent the trade off of intrusion injuries for deceleration injuries and vice versa in vehicles of different sizes.

TEST PROGRAM

The test program was developed with the following objectives:

- Evaluate use of the Renault PDB test method as a compatibility test.
- Evaluate the use of the PDB in a constant energy compatibility test procedure as detailed above in comparison to car-to-car test outcomes.
- Evaluate the use of a mobile PDB compatibility test procedure in comparison to a fixed PDB test.
- Provide input to IHRA for development of Compatibility test procedures.

The Progressive Deformable Barrier (PDB) (see Figure 2), designed by Renault [1] has been proposed for the assessment of vehicle aggressivity through assessment of the homogeneity or "flatness" of the crush profile of the PDB after a 60 km/h offset crash test. The PDB contains upper and lower load paths, which have different stiffness profiles in order to induce vertical shear in a vehicle. The element also has progressively increasing stiffness as it is deformed (achieved by chemical etching of the honeycomb). Use of this element in offset configuration induces lateral shear in the vehicle. The PDB is significantly deeper than the Offset Deformable Barrier (ODB) element that is currently used in regulatory and consumer offset test procedures [2]. This is intended to prevent "bottoming out" of the element, where the vehicle structure imparts force upon the structure supporting the element, achieving forces that would not realistically be produced by a real collision partner.

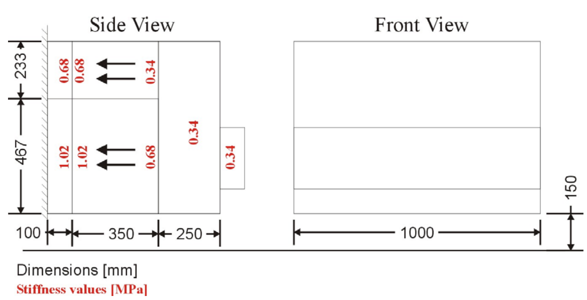

Figure 2. Layout of the Progressive Deformable Barrier (PDB)

The PDB was considered as a suitable means of evaluating the major criteria for a compatibility test proposal and was selected for both fixed and mobile barrier tests in this series. The original PDB proposal suggests a fixed element overlap of 750mm. This provides an overlap of between 41% and 45% for the selected subject cars. This is very close to the 40% measurement currently used in regulatory tests. For this reason an overlap of 40% was used for the fixed barrier tests in this test series.

A load cell array was used behind the PDB to measure longitudinal forces between the honeycomb and the supporting structure. From this it was hoped to obtain a relative picture of the stiffness profile of each vehicle (while recognising that the behaviour of the element has some effect on the measurements) and the crush behaviour of the PDB.

Phase 1

The two vehicles selected for the first phase of this program were:

Subaru Liberty RX – Passenger sedan (4 door), 4 cylinder horizontally opposed longitudinal engine and all wheel drive. Test mass was 1600kg (with 2 Hybrid III dummies).

Toyota Echo – 3 door hatchback (sold as "Yaris" in European markets), 4-cylinder inline transverse engine, offset to RHS, front wheel drive. Test mass was 1060kg.

These vehicles were both fairly new models and both had achieved a good (4 star) NCAP rating. The Liberty is not a particularly 'conventional' car in terms of drivetrain layout, with a very wide engine, however it was considered that since any test proposal would be applicable to all possible vehicle designs it was appropriate to use the Liberty.

A car-to-car test was conducted, followed by tests of both subject vehicles separately into mobile and fixed deformable barriers. All vehicles were right hand drive and impacted on the driver's side.

The Car-to-Car test was conducted as follows:

- Both vehicles moving at 50 km/h
- Overlap: 50% of width of narrower vehicle
- Instrumented Hybrid III dummies in driver and front passenger seats

The Car-to-MDB test was conducted as follows:

- Car and trolley moving at 50 km/h
- Overlap: 50% of width of vehicle
- Instrumented Hybrid III dummies in driver and front passenger seats
- PDB Element with load cell array fitted to trolley
- Trolley mass: 1620kg

The Car-to-fixed Barrier test was conducted as follows:

- Car moving at 60 km/h
- Overlap: 40% of width of vehicle
- Instrumented dummies
- PDB Element with load cell array, using typical ODB fixture

Phase 1 Results

<u>Vehicle Deformations</u> In the car-to-car test, the Echo was significantly deformed with notable collapse of the upper A-pillar and driver's side floorpan. While there was also significant deformation of the Echo in the car-to-mobile PDB test, this mode of deformation was very different, with the engine having been pushed rearward and intruding into the occupant cell, deforming the instrument panel beam and causing substantial movement of the centre console. On review of high-speed films it was found that due to tracking problems the mobile element had engaged more than 50% (about 54%) of the front of the Echo. Deformation to the Echo in the fixed PDB test was significantly less than previous tests, with little distortion of the right hand door aperture, A-pillar or floorpan.

Deformations for the Subaru Liberty showed much greater similarity between the car-to-car and car-to-fixed PDB tests. Alignment of the mobile PDB was again greater than 50% (about 56%) and the deformation mode of the vehicle was dissimilar to both car-to-car and car-to-fixed PDB, with substantial upward bending of the upper longitudinal. For this reason it is difficult to draw any further correlation between the MPDB test and other results in the series.

Any further tests using a mobile PDB should be conducted with 40% overlap since the outboard 10% of vehicles do not contain significant structural elements.

<u>Dummy Results</u> The dummy injury results for the Liberty and Echo show the mobile PDB test as being significantly more severe than either car-to-car or car-to-fixed barrier test. The fixed PDB test at

60 km/h has no injury values that are marginal or in excess of Injury Assessment Reference Values (IARVs). Contrasting that was the Echo's result in the car-to-car test against the Liberty where IARVs for head and chest were exceeded, with a marginal neck tension. The dummy results are summarised in Appendix 1.

Phase 2

Following the test of the Toyota Echo into a fixed PDB at 60 km/h in Phase 1, which showed little correlation to the car-to-car result in either injury measures or vehicle deformation, it was decided to investigate the concept of a constant energy test. It was decided to conduct each fixed PDB test at a speed that provided a test energy equivalent to the medium sized (1600 kg) Liberty at 60 km/h. Therefore the 1060 kg Echo was re-tested at an increased speed of 74 km/h.

As a result of the extensive occupant compartment deformation observed in the Echo in the car-to-car test in Phase 1, it was decided to include another vehicle of similar size that was designed with a more homogeneous front structure, with greater connection between front structural members. The new model Holden Barina (Opel Corsa in Europe) was chosen as it has extensive connection across the front of the vehicle and three load paths (subframe, lower longitudinal and upper longitudinal (shotgun)). The Barina (1220 kg test mass) was tested at 69 km/h.

The Ford Falcon AU II was included to examine the applicability of the PDB assessment method to a larger passenger vehicle, with longitudinal engine and rear wheel drive, which remains a very common configuration in the Australian vehicle fleet. The Ford Falcon, being slightly heavier than the Liberty, was therefore tested at a reduced speed of 57.7km/h.

The details of the two vehicles added to Phase 2 of this program are:

Holden Barina – 3 door hatchback, 4-cylinder inline transverse engine, offset to RHS and front wheel drive. Test mass was 1220 kg (with 2 Hybrid III dummies).

Ford Falcon AU II – 4 door sedan, 6-cylinder inline engine mounted north-south and rear wheel drive. Test mass was 1730 kg (with 2 Hybrid III dummies).

The Barina and the Falcon were each subjected to a car-to-car test against the medium sized Liberty (both vehicles travelling at 50 km/h; 50% overlap of the narrower vehicle). This was then supplemented with a car-to-fixed PDB test as described above.

Phase 2 Results

Vehicle Deformations Deformation measurements of the Barina to Liberty test and Barina to fixed PDB test were very similar and there appeared to be a good match in the deformation modes of the two tests (Figure 3).

In the Liberty to Falcon test, the Liberty overrode the Falcon's longitudinal (see highlighted area in Figure 4) and overwhelmed its upper load path causing the instrument panel and wheel/tyre assembly to intrude into the passenger compartment. This effect was not seen in the Falcon to PDB test, where the longitudinal has been bent upwards and the upper longitudinal remaining essentially intact. There was less passenger compartment intrusion in the PDB test than the car-to-car test.

As shown in Figure 5, the 74 km/h PDB test of the Toyota Echo produced a gross vehicle deformation

Figure 3 - Comparison of vehicle deformation - Barina v Liberty (left); v PDB (right).

Figure 4. Comparison of vehicle deformation - Falcon v Liberty (left); v PDB (right).

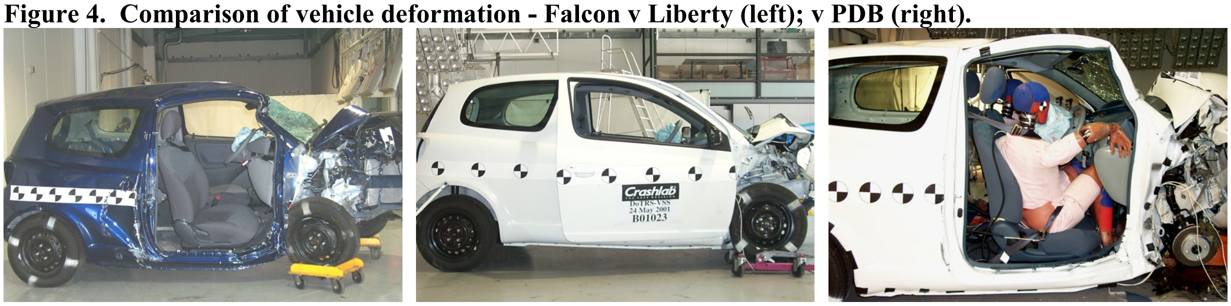

Figure 5. Comparison of vehicle deformation - Echo v Liberty (left); v PDB 60km/h (centre); v PDB 74km/h (right).

that was much closer to that observed in the Echo v Liberty car-to-car test. There were some differences, however, in the mode of deformation of the vehicle front structure (the car-to-car test exercised the Echo's upper load path more).

Dummy Results The car-to-car test of the Barina against the Liberty resulted in higher head injury measures in the Barina than the 69 km/h PDB test. This may be a result of differences in the airbag firing time which was observed from high-speed films.

The Liberty to Falcon car-to-car test recorded some lower leg loads that were close to (but not exceeding) the IARV. These were not duplicated in the PDB test, where lower leg loads were low, however, loads to the head and chest were somewhat increased, though still below the IARV.

The injury results in the 74 km/h PDB test of the Toyota Echo were reasonably close to the car-to-car test against the Liberty, although there was an increased HIC in the 74 km/h PDB test, as well as a significant increase in femur forces and knee displacements. The dummy results are summarised in Appendix 1.

Phase 3

The constant energy PDB tests of the Barina (69 km/h) and Echo (74 km/h) in Phase 2 indicated that the Barina would overwhelm the Echo in a car-to-car test. Phase 3 consisted of a car-to-car test between the Toyota Echo and Holden Barina to investigate the ability of the constant energy PDB test to predict this.

Phase 3 Results

Vehicle Deformation The Echo exhibited similar deformation to the Liberty car-to-car test and the 74 km/h PDB test, except to a lesser extent – A-pillar, sill rupture, floorpan distortion, toepan intrusion. The Barina had a small amount of A-pillar deformation but the front door could be opened without the aid of tools. There was minimal toepan intrusion and sill distortion.

Dummy Results All dummy injury measurements for the Barina were significantly below the IARV limits. The Echo driver was loaded in the head, neck and chest regions with IARVs exceeded for head acceleration and neck flexion, and marginal for chest acceleration and HIC.

Phase 4

The program was then extended to include a large 4WD, to further assess the applicability of this test procedure to vehicles of a wide range of size and mass. The increasing popularity of 4WDs in Australia also prompted evaluation of the PDB using one of these vehicles. The 4WD chosen was the Ford Explorer II Mk2. This version was a revision to the original Explorer II which was modified to improve its performance in the 64 km/h NCAP offset frontal test. The following tests were conducted:

- Ford Explorer vs Subaru Liberty
- Ford Explorer vs fixed PDB

The details of the Ford Explorer II Mk2 are:

Body-on-frame 4-door, V6 longitudinal mounted constant all wheel drive. Test mass 2174 kg (with 2 Hybrid III dummies). Test speed into the PDB 51.6 km/h.

Phase 4 Results

Vehicle Deformations Pre-test static alignment of the vehicles indicated that the front longitudinals should have engaged. In the test, the Liberty's longitudinal started to crush to about 150-200 mm from the front of the vehicle. It then appears that the Explorer's longitudinal started over-riding at this point and peeled back the inner guard of the Liberty until the strut tower was engaged. The strut tower and upper shotgun were pushed backwards deforming the A-pillar, IP area and B-pillar roof rail joint. There was no noticeable deformation of the Explorer's longitudinal although the frame rail kinked and bent downwards near the firewall area.

In the PDB test, the PDB was fully crushed by the Explorer's longitudinal without initiating crush of the longitudinal. Again the frame rail kinked and bent downwards but further rearwards, near the driver's seat.

Dummy Results In the car-to-car test, injury risk measures were significantly higher in the Liberty than in the Explorer, though no IARVs were exceeded. Chest acceleration was within 20% of the reference value and head acceleration was close to 20% of the IARV. All injury measures for the Liberty were well above those recorded in the PDB test. Injury measures for the Explorer were also generally low in the PDB test, however the chest deflection was within 20% of the IARV.

Load Cell Results

The tests using a deformable element (both fixed and mobile) used a load cell array. For the first five of these used load cells provided by NHTSA [3]. The load cells covered the entire rear face of the honeycomb element in a 7x6 array, with normal and shear forces being recorded. The dimension of each load cell was 146.1mm x133.4mm. The flanges of the honeycomb were bolted directly to corresponding load cell faces (top and bottom).

The remaining barrier tests (Falcon and Explorer) used a different array, purchased by DOTARS. The array contained 48 load cells, each of 125x125mm nominal size. The cells were mounted in an 8x6 array to cover the complete PDB element.

For the passenger cars maximum loads on any load cell are in the order of 40-45kN. By comparison similar load cells behind the thinner ODB element in a fairly typical NCAP test have recorded loads above 130kN. This suggests that the PDB is sufficiently deep and stiff that the vehicle structure does not load the mounting face directly. However the body-on-frame Explorer did 'bottom-out' the PDB element and recorded significantly higher loads (approximately 100kN peak force on an individual cell).

Shear loads are transmitted from the element to the load cells through friction with the element backing plate and through the mounting bolts. It was found that for load cells where there is no bolt, the transfer of shear was not reliable and that the shear measurements did not provide useful information.

Use of the load cells also allows the calculation of an axial force/deflection curve for each vehicle/element system. The honeycomb and its deflection characteristic form part of this system. As deflection is calculated from acceleration of the vehicle it is difficult to differentiate between crush of the vehicle and crush of the honeycomb. However the element is the same in each test, and therefore some comparison can be made between the behaviour of each vehicle. Figure 6 shows the Force v Deflection curves for all of the fixed barrier tests.

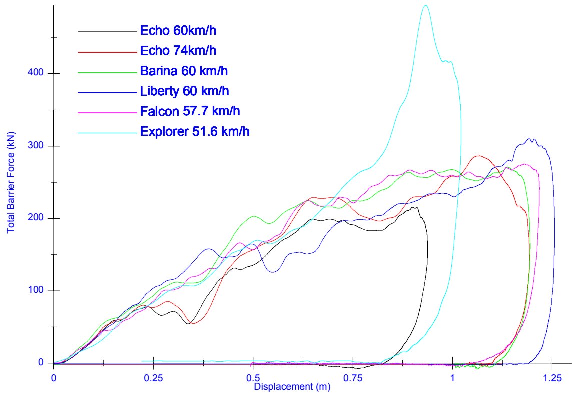

Figure 6. Force deflection plots

The area under the force / deflection curve is equivalent to work (or energy) – it can be seen in Figure 6 that the curve of the Echo test at 60 km/h (black) is of smaller area and that the remaining curves are of approximately equivalent area, as all but the 60 km/h Echo test were conducted with the same initial energy.

One of the suggested factors for improved vehicle compatibility is that the front structure of a vehicle should "offer increasing stiffness as penetration increases" [1]. It is notable in the overall force/deflection plots above that for the Barina and Liberty, which produced reasonable structural interaction, there is no significant drop in force through the crash sequence. By contrast the Echo shows a drop in force at approximately 250mm displacement (combined displacement of vehicle and element) and a further drop at approximately 750mm displacement which may be symptomatic of the less homogeneous front structure of the vehicle and/or insufficient passenger compartment stiffness.

DISCUSSION

Many observations in this program have related to deformation behaviour of the subject vehicle. In a feasible test for vehicle compatibility it is not necessary that the barrier element exactly replicate deformations of a subject vehicle when compared to car-to-car tests as this would lead to excessive "tuning" of the element to one particular crash configuration. However, it is important that the element presents a stiffness profile that is reasonably similar to other cars such that any changes to vehicle designs are applicable to real crashes.

The original Renault proposal suggests using the PDB to assess the aggressivity of a vehicle by evaluating the homogeneity or "flatness" of the crush profile of the PDB after a vehicle runs into it at 60 km/h and an overlap of 750mm (this presents a constant volume of the barrier to all impacting vehicles). However, this means that the percentage overlap will vary with the overall width of the each vehicle. It also means that vehicles of differing masses will impact the PDB with different energies so that heavier vehicles will crush the PDB to a greater depth. The assessment method needs to take these issues into account. Another assessment criterion might be to measure the load behind the PDB during the test to:

- Calculate the average height of force and using it as an indicator of the likelihood of overriding.
- Use the force/time history to assess homogeneity.

Use of an energy equivalent test speed appeared to improve the correlation between vehicle deformations of the fixed barrier and car-to-car tests. The PDB test appears to produce fairly similar vehicle deformations to the baseline car-to-car test in vehicles with a more homogeneous front structure, where there is greater connection between frontal structures.

The Toyota Echo was chosen for Phase 1 because it had been shown to perform well in the ECE R94/01 ODB test and the NCAP ODB test at the higher speed of 64 km/h. However, the results of the car-to-car tests in Phases 1 and 3 indicated that this performance was not necessarily repeated when the Echo crashed into other vehicles, even though one of the tests was into a vehicle in the same size class (Holden Barina). Testing in Europe of the Echo into the Renault Clio II further supported this.

It is possible that a car to car test of the Echo and Barina at a higher speed may have produced deformations of both vehicles that were a closer match to those seen in the constant energy fixed PDB tests.

Average Height Of Force

The US NHTSA has proposed a compatibility metric denoted as the Average Height of Force (AHOF) [4]. This proposed metric is derived from load cell measurements during full frontal vehicle tests against a rigid barrier fitted with load cells.

For vehicle to barrier tests conducted as part of the present study, this metric has been calculated from the data obtained from the load cells mounted behind the PDB. It should be borne in mind that the PDB has a stiffer lower zone and a softer upper zone, which preclude a direct comparison of AHOF measurements with those obtained on a rigid wall, because the upper zone can transmit less force than the lower zone and hence introduces a bias into the calculated AHOF result. The stiff lower zone has a ground clearance of 150 mm and a height of 467 mm (i.e. 617 mm from the ground); the upper zone commences at 617 mm from the ground and is 233 mm high. The AHOF results calculated from the PDB tests are shown in Table 1.

Table 1. Average Height of Force

Vehicle	Test Speed [km/h]	Test Mass [kg]	AHOF [mm]	Height of Centre of Pressure [mm]
Echo	60	1060	430.2	467
Barina	69	1220	421.6	512
Liberty	60	1600	458.6	512
Echo	74	1060	457.1	477
Falcon	57.7	1730	435.4	491
Explorer	51.6	2174	480.3	559

The results show that the Ford Explorer has the highest AHOF (480mm) whilst the other vehicles have AHOF results ranging from 421mm to 458mm. This is not unexpected, since the Explorer has a body-on-frame design with a relatively high ground clearance of the frame, whereas the other vehicles are all unibody-structure passenger cars.

Notably, the results for the Echo vary by almost 20mm with an increase in test speed. This may be due to the crushing of some structures and a consequent engagement of some higher structures in the 74 km/h test that did not occur in the 60 km/h test due to the lower energy. This demonstrates that the AHOF parameter is sensitive to the test speed and casts some doubt on the ability to characterise vehicle structures with a single parameter and predict compatibility of vehicle structures across a wide range of real-world crash conditions.

The NHTSA have proposed that the AHOF be limited to a maximum value. This would promote the design of vehicle structures at heights below the threshold and may initially improve the marked disparity between LTVs and passenger cars. However, it will not necessarily improve the interaction of all vehicles that meet this requirement. For example, in Table 1, if the AHOF were to be limited to 460mm, the Explorer would require modification to provide load bearing structures with a reduced ground clearance, however, the other vehicles in this study would not require changes and the existing incompatibility between these vehicles would remain. Hence, the AHOF only partially addresses compatibility, with the effectiveness dependent upon the structural height disparity in the fleet and the threshold value chosen.

This AHOF calculation has been applied to a similar set of offset crash test data which used the conventional EEVC deformable element, without the stratification of stiffness present in the PDB. Again the method appeared to be able to differentiate an SUV as having a higher AHOF than passenger cars that were tested, but this difference was quite small and it would be difficult to propose a limit based on this type of test.

Table 1 also reports the height of centre of pressure as determined by Renault using the deformed volume of the PDB. The Explorer has the highest centre of pressure, consistent with the AHOF metric, however, the other vehicles are ranked differently by the centre of pressure and AHOF metrics. This may be due to the fact that the AHOF is weighted by the time-dependent force function, whereas the centre of pressure is a function of the final deformation of the PDB.

TRL Homogeneity Analysis

The UK Transport Research Laboratory (TRL) has proposed a compatibility assessment based on a vehicle crash test into a full width rigid barrier, fitted with load cells and an aluminium honeycomb face [5]. The forces recorded on the load cells are smoothed and summed and then divided equally across an area denoted as a “standard footprint” to determine the desirable force (‘target load’) on each load cell within this footprint. The smoothed peak values recorded on the load-cell wall are compared to the desired (target) value and a variance of these values is calculated. This variance is calculated across all cells as well as for rows and columns to provide three homogeneity metrics for overall, row and columnar force distribution.

This homogeneity analysis method has been applied to the load cell measurements recorded behind the

PDB in the DOTARS test series. The vehicle footprint applied was necessarily different for the NHTSA and DOTARS load cell arrays. The (pre-smoothed) footprints were as follows:

- NHTSA – 5x4 cells 296mm (above ground) to 789mm x 756mm wide
- DOTARS – 6x4 cells 225mm (above ground) to 725mm x 750 wide

The different load cell arrays used during this test series make it difficult to directly compare tests with different load cells, however they should be broadly comparable, bearing in mind that the target zone for the NHTSA array was approximately 60mm higher off the ground. The results of the TRL homogeneity analysis are shown in Table 2. A lower value indicates greater homogeneity.

Table 2. TRL Homogeneity Analysis.

Vehicle	Array	Homogeneity		
		Cell	Row	Column
Echo 60 km/h	NHTSA	37.8	28.1	26.1
Barina	NHTSA	74.5	50.5	50.6
Liberty	NHTSA	57.7	44.0	45.2
Echo 74 km/h	NHTSA	82.3	64.5	74.3
Falcon	DOTARS	28.4	20.7	24.8
Explorer	DOTARS	298	30.5	248

The results of the TRL homogeneity analysis show that the Explorer is the most inhomogeneous of the tested vehicles in terms of overall and columnar behaviour. However it was surprisingly homogeneous with respect to rows. This suggests that the vertical stiffness variation across the front structure of the Explorer is much less than the horizontal variation.

Notably the TRL analysis ranks the Echo at 60 km/h and 74 km/h quite differently. This may be indicative of a sensitivity to test speed (impact energy) for a given vehicle.

It is possible that this preliminary analysis is affected by load smearing or bridging of load cells. The stiff lower and less-stiff upper load paths of the PDB may also influence the results.

Deformation of PDB

The Ford Explorer 'bottomed out' the PDB element, with consequent concentration of load-cell forces. While this may be contrary to the design intent of the PDB, this should be taken in context of the assessment methods outlined below which would identify this vehicle as not having the required characteristics for vehicle compatibility.

Renault analysis Renault has proposed a technique to assess the behaviour of the front structure of a vehicle by conducting a dynamic crash test into a PDB and examining the deformation profile of the PDB. It should be noted that this analysis technique is still under development and is not yet a fully defined and firm proposal, but has been applied to this test series to investigate the validity of the current algorithm.

The assessment technique involves digitising the deformed surface of the PDB and analysing this data with a numerical algorithm. The deformation of the barrier in the direction of travel of the impacting vehicle is divided into 50 mm contour intervals (as shown in Appendix 2). For each contour region, the area, average depth of deformation and the height of the centre of pressure above the ground are calculated. These three measurements are used to characterise the vehicle front structure.

The depth of deformation provides an indication of the force imparted by the vehicle structure onto the PDB. This depth is compared against a reference depth of 300 mm.

The height of the centre of pressure has some similarity to the AHOF metric as proposed by the NHTSA. The values of the height of centre of pressure shown in Table 1 are single characteristic values for the total deformed volume. The height of the centre of pressure can also be calculated for each contour region. These heights are compared against a reference value of 420 mm (determined by EEVC WG 15 as the average ground clearance of the longitudinal structural members of European vehicles).

The area of each contour region is considered significant as it quantifies the size of the region deformed within a particular contour value. A large area of deep intrusion is considered to be worse than a small area of deep intrusion. However, if a vehicle is able to spread a given load over a larger area, this should result in reduced intrusion into the barrier and therefore a more favourable rating.

The Renault algorithm combines the measurements of depth, height and area of each contour region to calculate a single characteristic value for each contour region. These characteristic values for each contour region are then combined to provide an overall vehicle assessment.

The results from the Renault algorithm are as shown in Table 3:

Table 3. Results from Renault Algorithm

Vehicle	Test Speed [km/h]	Test Mass [kg]	Vehicle Results (Renault algorithm)]
Echo	60	1060	3.1
Barina	69	1220	4.8
Liberty	60	1600	7.4
Echo	74	1060	3.4
Falcon	57.7	1730	5.1
Explorer	51.6	2174	10.4

The similarity of results for the Echo at 60 km/h and 74 km/h suggest that test speed has a minor influence on the calculated metric. However, with the exception of the Subaru Liberty, increased mass seems to be correlated with an increased value of the metric, despite the fact that the tests were conducted with equivalent initial kinetic energy. This apparent dependence of the results on test mass may be a reflection of the fact that the stiffness of the front structures of these vehicles has been indirectly controlled by existing regulatory and/or consumer crash testing. Therefore the correlation with mass may be indicative of a correlation with stiffness which may explain the high result for the Liberty.

Comparison of deformation contours with peak force contours A number of organisations that have conducted tests using a load cell barrier face behind a deformable honeycomb element have suggested that it is not possible to measure an accurate force distribution [5]. The suggested likely causes of this are load concentration due to irregularity of the load cell face as well as 'smearing' resulting from the shear strength of the honeycomb. This has been demonstrated on load cell arrays in both full width and offset configuration using impactors of a simple known structure.

Compatibility assessments have been proposed [1, 4], which utilise forces measured on the barrier and/or deformation of the deformable element as an input. Hence, an attempt has been made to qualitatively assess the correlation between forces measured on the load cells behind the PDB and deformation of the PDB in this test series.

It is assumed that the maximum deformation of any point on the PDB is a result of the peak force at that point at any time during the crash test. Therefore, a comparison was made of the deformation profile of the PDB and the peak force recorded at each load cell.

Appendix 3 shows a series of contour plots for each of the PDB tests. Each plot shows the peak load cell forces represented by a series of magnitude-dependent coloured contour lines. Superimposed on each contour plot is the corresponding PDB deformation, represented by a series of points with deformation magnitude denoted by colour.

In general, regions of high force coincide with regions of high deformation, however, there are some anomalies. For example, the contour plot for the Falcon shows areas of high deformation that do not have corresponding high forces measured on the load cells. This may be due to the action of PDB deformation mechanisms other than crushing. Cutting, bending or lateral shearing of the honeycomb could result in deformation in the absence of a corresponding axial force measured on the load cells.

This suggests that in some cases deformations may yield similar information to load cell measurements, however, deformations may contain extraneous data.

The contour plot for the 60 km/h Echo shows an area of comparatively high force without corresponding high deformation. Examination of the vehicle and barrier suggest that this is due to the wheel assembly, which may initially contact only a small area of the barrier, but would progressively spread load across a larger area. The deformation of the PDB shows a broad shallow indentation consistent with this concept.

A consequent spreading of load measured on the load cells would be expected, however this is not evident in the peak values. It would appear that the distributed load on the PDB has been recorded as a concentrated load on a single load cell. One possible explanation for this would be if one load cell was slightly proud of its neighbours, such that the distributed load on the honeycomb is supported primarily on a single load cell.

Comparison of Compatibility Assessment Methods

Average Height of Force, Height of Centre of Pressure, TRL Homogeneity Analysis and the Renault analysis all identify the Explorer as having design characteristics that are undesirable for vehicle compatibility. However, the various analyses are not in agreement with regard to the compatibility aspects of the other (passenger) vehicles tested. Some techniques indicate that the Barina is 'more compatible' than the Echo and the relative rankings of the Falcon and Liberty also vary considerably.

This may be a reflection of slight variation in the test results due to a change in load cell arrays, or may also be due to the inappropriate use of some analysis techniques with load cell data collected behind the PDB.

Application of Proposed Test Methods

The Australian research recommends a suite of 3 tests for improving compatibility without sacrificing self-protection:

1. A constant energy compatibility test using the PDB and setting injury criteria (222 kJ baseline energy)

2. An ODB self-protection test at 60 km/h

3. A full width self-protection test at 56 km/h

It is expected that not all 3 tests may be needed for all vehicle classes.

Further work needs to be done to develop an agreed method of using the deformation profile and load cell data to improve the structural interaction (geometric and stiffness matching) by:

- Maximising homogeneity of the front end.
- Limiting the force transferred to the impact partner.

It is expected that compatibility countermeasures will differ depending upon vehicle class. Therefore it is necessary to define small, medium and large vehicles in terms of mass breakpoints. The masses in square brackets are a first proposal for these and are test masses including two Hybrid III dummies, test equipment and fluids to current regulatory requirements.

Small Vehicles [< 1300 kg] The use of a constant energy PDB test with injury criteria appears to be able to improve the compatibility of smaller vehicles in terms of structural interaction, passenger compartment stiffness and restraint system design. The main priority here is probably to increase passenger compartment stiffness. A full width barrier test is still required to ensure the vehicle is not too stiff and is capable of protecting the occupants in a high deceleration crash. It is questionable whether an ODB test would add any value because the PDB test should have covered intrusion-based injuries due to comparatively high test speed of these vehicles into the PDB.

Medium Vehicles [1300 – 1600 kg] The use of a constant energy PDB test with injury criteria appears to be able to improve the compatibility of medium vehicles in terms of structural interaction and probably passenger compartment stiffness. There is a need to maximise homogeneity for efficient use of limited crush space as well as minimising the transfer force to the crash partner. The challenge for designers of this vehicle class appears to be improving the compatibility of medium sized vehicles with smaller ones without sacrificing the medium vehicle's ability to cope with crashes against larger vehicles. Probably both an ODB and a full width barrier test are still required to ensure the vehicle and restraint system design has achieved a balance between protection against intrusion and deceleration-based injuries.

Large Vehicles [> 1600 kg] The use of a constant energy PDB test with injury criteria appears to be able to improve the compatibility of larger vehicles in terms of maximising structural interaction and reducing front end stiffness to accommodate smaller crash partners. There is a need to maximise homogeneity for efficient use of the foremost part of the crush structure to minimise the transfer force to the crash partner. The challenge for designers of this vehicle class appears to be improving the compatibility with small and medium-sized vehicles without sacrificing the large vehicle's ability to cope with crashes against similar sized vehicles. Probably both an ODB and a full width barrier test are still required to ensure the vehicle and restraint system design has achieved a balance between protection against intrusion and deceleration-based injuries after having been redesigned for improved compatibility.

CONCLUSIONS/FURTHER WORK

It is believed that the suite of 3 tests proposed in this paper has the potential to improve compatibility without sacrificing self-protection, viz:

1. A constant energy compatibility test using the PDB and setting injury criteria (222 kJ baseline energy). The deformation/load cell data recorded would be used to provide a homogeneity rating and to limit the load transfer to the crash partner.

2. An ODB self-protection test at 60 km/h.

3. A full width self-protection test at 56 km/h.

However, further research is required to:

- Establish how a homogeneity rating will drive vehicle design to improve compatibility and how best to measure this.
- Establish an agreed load transfer limit to the other impact partner which is achievable for vehicles of different classes.
- Examine how the compatibility of dissimilar vehicles would be affected if they were designed to the suite of tests suggested. This could be done using finite element modelling in a series of parametric studies changing vehicle design characteristics.

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APPENDIX 1. DUMMY MEASUREMENTS

	Subaru Liberty					
	v Echo B01019	v MPDB B01020	v Barina B01022	v PDB B01026	v Falcon B01039	v Explorer B02036
Driver						
HIC36	167.3	444.26	223.34	261.91	264.86	706.72
HIC15	95.43	273.15	154.77	132.69	159.85	410.02
Head Accel 3ms clip [g]	34.3	53.62	42.18	39.31	57.84	63.32
Peak Neck Fx [kN]	-0.58	0.72	-0.46	-0.63	-0.64	-0.89
Peak Neck Fy [kN]	-0.19	-0.32	-0.34	-0.35	-0.25	-0.53
Peak Neck Fz [kN]	0.86	1.98	1.04	1.2	1.07	2.06
Peak Neck Mx [Nm]	-14.97	-24.12	-28.81	-29.06	-19.25	26.13
Peak Neck My Extension* [Nm]	-11.88	-24.12	-13.18	-17.5	-30.8	-24.18
Peak Neck Mz [Nm]	-13.72	-18.92	23.93	-25.67	-13.19	-10.88
Chest Resultant Accel 3ms [g]	33.38	47.27	39.94	30.75	33.77	52.6
Peak Chest Deflection [mm]	-29.8	-33.8	-28.4	-31.1	-23.3	-35.9
V*C [m/s]	0.15	0.24	0.17	0.14	0.1	0.39
Peak Left Femur Force [kN]	-0.69	-4.67	-0.68	-0.36	-0.55	-6.08
Peak Right Femur Force [kN]	-0.11	-1.73	-0.3	-0.37	-0.18	-1.34
Peak Left Knee Slider Disp [mm]		-7		-0.14		-1.76
Peak Right Knee Slider Disp [mm]		-2.23		-0.02		-6.29
Peak Left Upper TI		0.32		0.19		0.37
Peak Left Lower TI		0.58		0.33		0.4
Peak Right Upper TI		0.47		0.34		0.54
Peak Right Lower TI		0.58		0.2		0.55
Peak Lap Belt Load [kN]		9.02		5.52		
Peak Sash Belt Load [kN]		4.94		5.15		9.35
Passenger						
HIC36	106.52	357.11	141.98	178.05	178.12	257.02
HIC15	60.58	189.34	94.94	93.73	102.41	148.79
Head Accel 3ms clip [g]	28.34	44.97	35.11	33.84	34.49	41.39
Chest Resultant Accel 3ms [g]	27.65	41.88	32.1	25.08	29.97	30.34
Peak Chest Deflection [mm]	-25	-29.4	-22.6	-28.8	-19.1	-26.4
V*C [m/s]	0.13	0.16	0.1	0.11	0.06	0.1
Peak Left Femur Force [kN]		-0.45		-0.26		-0.22
Peak Right Femur Force [kN]		-1.52		-0.15		-1.06

* includes values recorded during rebound

Key

<80% of IARV	Within ± 20% IARV	>120% of IARV

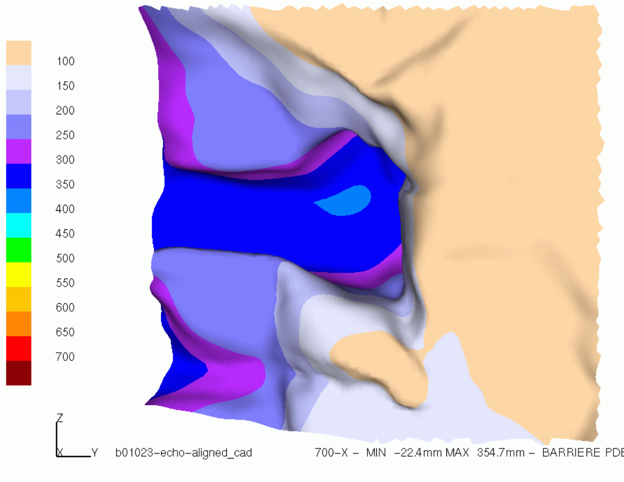
	Toyota Echo				
	v Liberty B01019	v MPDB B01021	v PDB (60) B01023	v PDB (74) B01029	v Barina B02007
Driver					
HIC36	945.03	1621.31	513.49	1303.75	914.24
HIC15	833.34	1615.75	320.38	1078.6	735.19
Head Accel 3ms clip [g]	93.28	132.21	55.91	91.07	84.36
Peak Neck Fx [kN]	-0.72	-1.54	0.14	-0.72	-0.61
Peak Neck Fy [kN]	0.47	0.44	0.07	0.6	0.53
Peak Neck Fz [kN]	3.18	5.19	1.78	5.09	2.59
Peak Neck Mx [Nm]	-58.75	18.98	-23.14	-36.93	23.96
Peak Neck My Extension* [Nm]	-79.64	-108.16	-30.39	-65.86	-59.25
Peak Neck Mz [Nm]	54.4	33.43	-12.31	44.21	15.71
Chest Resultant Accel 3ms [g]	64.58	63.69		60.09	48.39
Peak Chest Deflection [mm]	-21.7	-39.8	-30.9	-33	-31.8
V*C [m/s]	0.15	0.72	0.13	0.28	0.29
Peak Left Femur Force [kN]	-1.98	-12.96	-1.25	-4.95	-0.78
Peak Right Femur Force [kN]	-2.09	-9.82	-1.37	-6.31	-0.61
Peak Left Knee Slider Disp [mm]	-4.82	-17.93	-2.01	-19.91	-2.38
Peak Right Knee Slider Disp [mm]	-4.29	-22.64	-5.52	-8.19	-1.3
Peak Left Upper TI	0.88	1.6	0.35	1.48	0.4
Peak Left Lower TI	0.35	0.61	0.17	0.32	0.38
Peak Right Upper TI	0.5	1.69	0.42	1.02	0.41
Peak Right Lower TI	0.46	0.9	0.88	0.84	0.56
Peak Lap Belt Load [kN]	9.33	10.07	6.82	9.82	10.49
Peak Sash Belt Load [kN]	5.69	5.61	5.31	5.78	5.63
Passenger					
HIC36	409.04	1133.77	257.19	553.67	323.8
HIC15	195.91	815.1	134.9	276.35	180.08
Head Accel 3ms clip [g]	45.96	97.55	37.64	53.76	45.77
Chest Resultant Accel 3ms [g]	36.93	48.42	27.41	34.1	36.37
Peak Chest Deflection [mm]	-35.8	-41.3	-38.4	-39.1	-39.6
V*C [m/s]	0.19	0.25	0.15	0.18	0.29
Peak Left Femur Force [kN]	-1.08	-1.96	-0.74	-1.75	-1.41
Peak Right Femur Force [kN]	-1.6	-2.88	-2.11	-2.59	-1.57

* includes values recorded during rebound

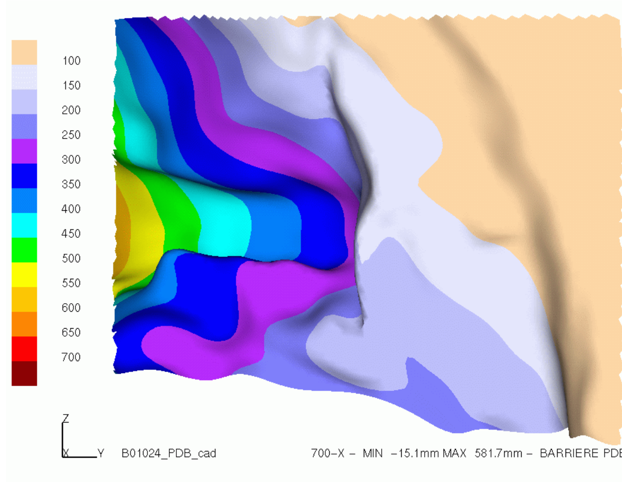
	Holden Barina			Ford Falcon AUII		Ford Explorer II Mk2	
	v Liberty B01022	v PDB B01024	v Echo B02007	v Liberty B01039	v PDB B01061	v Liberty B02036	v PDB B02037
Driver							
HIC36	844.19	409.71	359.01	293.94	539.72	370.96	186.26
HIC15	679.08	241.31	235.96	213.35	415.59	248.96	104.49
Head Accel 3ms clip [g]	75.65	49.97	48.35	47.96	65.74	50.76	36.28
Peak Neck Fx [kN]	-0.57	-0.28	-0.28	-0.45	-0.51	-0.35	-0.48
Peak Neck Fy [kN]	0.16	-0.98	-0.35	-0.29	-0.22	-0.42	-0.33
Peak Neck Fz [kN]	2.95	2.05	1.98	1.52	1.85	1.35	1.1
Peak Neck Mx [Nm]	-59.09	-81.6	-33.5	30.21	30.62	39.9	-29.35
Peak Neck My Extension* [Nm]	-56.81	-36.31	-29.86	-21.52	-11.82	-14.9	-33.37
Peak Neck Mz [Nm]	18.45	30.83	18.2	-17.88	-23.23	-14.05	-24.14
Chest Resultant Accel 3ms [g]	62.41	47.71	44.95	36.88	37.67	34.21	32.35
Peak Chest Deflection [mm]	-30.4	-25.8	-28.3	-27	-40.1	-32.6	-42.2
V*C [m/s]	0.18	0.15	0.22	0.17	0.31	0.23	0.34
Peak Left Femur Force [kN]	-6.79	-3.62	-5.76	-4.34	-0.66	-2.2	-1.6
Peak Right Femur Force [kN]	-2.87	-3.85	-1.57	-1.92	-0.54	-1.94	-1.72
Peak Left Knee Slider Disp [mm]	-5.86	-6.01	-1.43	-7.11	-0.17	0	-0.39
Peak Right Knee Slider Disp [mm]	-3.59	-4.63	-0.61	-1.91	-0.47	-0.02	-0.16
Peak Left Upper TI	0.61	0.55	0.43	0.86	0.36	0.56	0.2
Peak Left Lower TI	0.44	0.23	0.39	1.05	0.13	0.69	0.2
Peak Right Upper TI	0.63	0.38	0.61	0.74	0.43	0.66	0.38
Peak Right Lower TI	0.35	0.21	0.54	1.19	0.28	0.11	0.36
Peak Lap Belt Load [kN]	7.39	6.63	7.55	14.16	16.52	5.6	5.52
Peak Sash Belt Load [kN]	6.74	6	7.08	16.07	5.53	5.73	6.01
Passenger							
HIC36	545.57	469.39	262.63	123.56	267.68	255.78	218.64
HIC15	394.97	310.88	147.18	55.36	179.9	149.08	120.5
Head Accel 3ms clip [g]	63.04	55.19	39.99	27.05	45.15	41.98	37.3
Chest Resultant Accel 3ms [g]	40.73	39.47	46.54	22.85	23.89	26.95	27.36
Peak Chest Deflection [mm]	-30.4	-34.9	-33.2	-31.6	-34.3	0	-31
V*C [m/s]	0.2	0.17	0.25	0.15	0.54	0.1	0.11
Peak Left Femur Force [kN]	-1.4	-0.27	-0.19	-0.16	-0.14	-0.14	-0.19
Peak Right Femur Force [kN]	-2.53	-2.24	-2.89	-1.79	-0.08	-0.26	-0.09

* includes values recorded during rebound

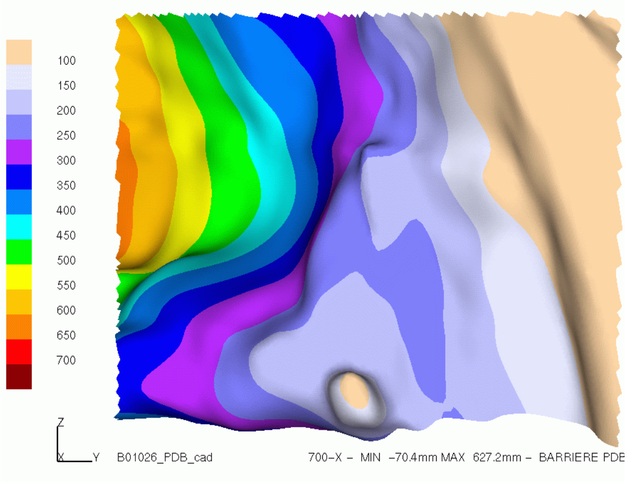
APPENDIX 2. PDB DEFORMATION PROFILES



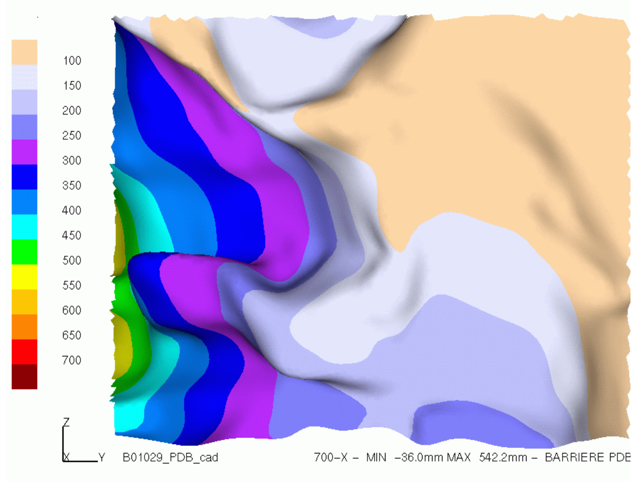
B01023 – Echo 60 km/h



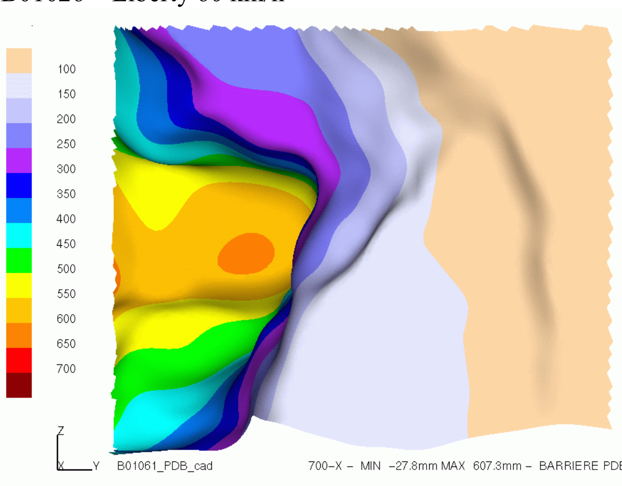
B01024 – Barina 69 km/h



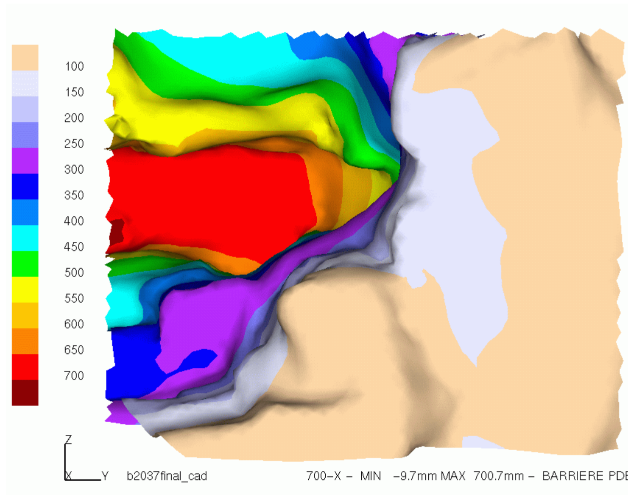
B01026 – Liberty 60 km/h



B01029 – Echo 74 km/h



B01061 – Falcon 57.7 km/h



B02037 – Explorer 51.6 km/h

APPENDIX 3. COMPARISON OF DEFORMATION CONTOURS WITH PEAK FORCE CONTOURS